The Silurian Hypothesis: Would it be possible to detect an industrial civilization in the geological record?

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Abstract

If an industrial civilization had existed on Earth many millions of years prior to our own era, what traces would it have left and would they be detectable today? We summarize the likely geological fingerprint of the Anthropocene, and demonstrate that while clear, it will not differ greatly in many respects from other known events in the geological record. We then propose tests that could plausibly distinguish an industrial cause from an otherwise naturally occurring climate event.

Keywords: Astrobiology – Drake Equation – industrial civilization – Silurian hypothesis – Anthropocene – PETM

1 INTRODUCTION

The search for life elsewhere in the universe is a central occupation of astrobiology and scientists have often looked to Earth analogues for extremophile bacteria, life under varying climate states and the genesis of life itself. A subset of this search is the prospect for intelligent life, and then a further subset is the search for civilizations that have the potential to communicate with us. A common assumption is that any such civilization must have developed industry of some sort. In particular the ability to harness those industrial processes to develop radio technologies capable of sending or receiving messages. In what follows, however, we will define industrial civilizations here as the ability to harness external energy sources at global scales.

One of the key questions in assessing the likelihood of finding such a civilization is an understanding of how often, given that life has arisen and that some species are intelligent, does an industrial civilization develop? Humans are the only example we know of, and our industrial civilization has lasted (so far) roughly 300 years (since, for example, the beginning of mass production methods). This is a small fraction of the time we have existed as a species, and a tiny fraction of the time that complex life has existed on the Earth's land surface (∼400 million years ago, Ma). This short time period raises the obvious question as to whether this could have happened before. We term this the "Silurian Hypothesis"[1].

While much idle speculation and late night chatter has been devoted to this question, we are unaware of previous serious treatments of the problem of detectability of prior terrestrial industrial civilizations in the geologic past. Given the vast increase in work surrounding exoplanets and questions related to detection of life, it is worth addressing the question more formally and in its astrobiological setting. We note also the recent work of Wright (2017) which addressed aspects of the problem and previous attempts to assess the likelihood of solar system non-terrestrial civilization such as Haqq-Misra & Kopparapu (2012). This paper is an attempt to remedy the gap in a way that also puts our current impact on the planet into a broader perspective. We first

[1]We name the hypothesis after a 1970 episode of the British science fiction TV series Doctor Who where a long buried race of intelligent reptiles "Silurians" are awakened by an experimental nuclear reactor. We are not however suggesting that intelligent reptiles actually existed in the Silurian age, nor that experimental nuclear physics is liable to wake them from hibernation. Other authors have dealt with this possibility in various incarnations (for instance, Hogan (1977)), but it is a rarer theme than we initially assumed.

note the importance of this question to the well-known Drake equation. Then we address the likely geologic consequences of human industrial civilization and then compare that fingerprint to potentially similar events in the geologic record. Finally, we address some possible research directions that might improve the constraints on this question.

1.1 Relevance to the Drake Equation

The Drake equation is the well-known framework for estimating of the number of active, communicative extraterrestrial civilizations in the Milky Way galaxy (Drake, 1961, 1965). The number of such civilizations, N, is assumed to be equal to the product of; the average rate of star formation, R^*, in our galaxy; the fraction of formed stars, f_p, that have planets; the average number of planets per star, n_e, that can potentially support life; the fraction of those planets, f_l, that actually develop life; the fraction of planets bearing life on which intelligent, civilized life, f_i, has developed; the fraction of these civilizations that have developed communications, f_c, i.e., technologies that release detectable signs into space, and the length of time, L, over which such civilizations release detectable signals.

$$N = R^* \cdot f_p \cdot n_e \cdot f_\ell \cdot f_i \cdot f_c \cdot L$$

If over the course of a planet's existence, multiple industrial civilizations can arise over the span of time that life exists at all, the value of f_c may in fact be greater than one.

This is a particularly cogent issue in light of recent developments in astrobiology in which the first three terms, which all involve purely astronomical observations, have now been fully determined. It is now apparent that most stars harbor families of planets (Seager, 2013). Indeed, many of those planets will be in the star's habitable zones (Howard, 2013; Dressing & Charbonneau, 2013). These results allow the next three terms to be bracketed in a way that uses the exoplanet data to establish a constraint on exo-civilization pessimism. In Frank & Sullivan (2016) such a "pessimism line" was defined as the maximum "biotechnological" probability (per habitable zone planets) f_{bt} for humans to be the only time a technological civilization has evolved in cosmic history. Frank & Sullivan (2016) found f_{bt} in the range $\sim 10^{-24}$ to 10^{-22}.

Determination of the "pessimism line" emphasizes the importance of 3 Drake equation terms f_ℓ, f_i and f_c. Earth's history often serves as a template for discussions of possible values for these probabilities. For example the has been considerable discussion of how many times life began on Earth during the early Archean given the ease of abiogenisis (Patel et al., 2015) including the possibility of a "shadow biosphere" composed of descendants of a different origin event from the one which led to our Last Universal Common Ancestor (LUCA) (Cleland & Copley, 2006). In addition, there is a long standing debate concerning the number of times intelligence has evolved in terms of dolphins and other species (Marino, 2015). Thus only the term f_c has been commonly accepted to have a value on Earth of strictly 1.

1.2 Relevance to other solar system planets

Consideration of previous civilizations on other solar system worlds has been taken on by Wright (2017) and Haqq-Misra & Kopparapu (2012). We note here that abundant evidence exists of surface water in ancient Martian climates (3.8 Gya) (e.g. Achille & Hynek, 2010; Arvidson et al., 2014), and speculation that early Venus (2 Gya to 0.7 Gya) was habitable (due to a dimmer sun and lower CO_2 atmosphere) has been supported by recent modeling studies (Way et al., 2016). Conceivably, deep drilling operations could be carried out on either planet in future to assess their geological history. This would constrain consideration of what the fingerprint might be of life, and even organized civilization (Haqq-Misra & Kopparapu, 2012). Assessments of prior Earth events and consideration of Anthropocene markers such as those we carry out below will likely provide a key context for those explorations.

1.3 Limitations of the geological record

That this paper's title question is worth posing is a function of the incompleteness of the geological record. For the Quaternary (the last 2.5 million years), there is widespread extant physical evidence of, for instance, climate changes, soil horizons, and archaeological evidence of non-Homo Sapiens cultures (Denisovians, Neanderthals etc.) with occasional evidence of bipedal hominids dating back to at least 3.7 Ma (e.g. the Laetoli footprints) (Leakey & Hay, 1979). The oldest extant large scale surface is in the Negev Desert and is approximately 1.8Ma old (Matmon et al., 2009). However, pre-Quaternary land-evidence is far sparser, existing mainly in exposed sections, drilling, and mining operations. In the ocean sediments, due to the recycling of ocean crust, there only exists sediment evidence for periods that post-date the Jurassic (∼170Ma) (ODP Leg 801 Team, 2000).

The fraction of life that gets fossilized is always extremely small and varies widely as a function of time, habitat and degree of soft tissue versus hard shells or bones (Behrensmeyer et al., 2000). Fossilization rates are very low in tropical, forested environments, but are higher in arid environments and fluvial systems. As an example, for all the dinosaurs that ever lived, there are only a few thousand near- complete specimens, or equivalently only a handful of individual animals across thousands of taxa per 100,000 years. Given the rate of new discovery of taxa of this age, it is clear that species as short-lived as Homo Sapiens (so far) might not be represented in the existing fossil record at all.

The likelihood of objects surviving and being discovered is similarly unlikely. Zalasiewicz (2009) speculates about preservation of objects or their forms, but the current area of urbanization is less than 1% of the Earth's surface (Schneider et al., 2009), and exposed sections and drilling sites for pre-Quaternary surfaces are orders of magnitude less as fractions of the original surface. Note that even for early human technology, complex objects are very rarely found. For instance, the Antikythera Mechanism (ca. 205 BCE) is a unique object until the Renaissance. Despite impressive recent gains in the ability to detect the wider impacts of civilization on landscapes and ecosystems (Kidwell, 2015), we conclude that for potential civilizations older than about 4 Ma, the chances of finding direct evidence of their existence via objects or fossilized examples of their population is small. We note, however, that one might ask the indirect question related to antecedents in the fossil record indicating species that might *lead* downstream to the evolution of later civilization-building species. Such arguments, for or against, the Silurian hypothesis would rest on evidence concerning highly social behavior or high intelligence based on brain size. The claim would then be that there are other species in the fossil record which could, or could not, have evolved into civilization-builders. In this paper, however, we focus on physico-chemical tracers for previous industrial civilizations. In this way there is an opportunity to widen the search to tracers that are more widespread, even though they may be subject to more varied interpretations.

1.4 Scope of this paper

We will restrict the scope of this paper to geochemical constraints on the existence of pre-Quaternary industrial civilizations, that may have existed since the rise of complex life on land. This rules out societies that might have been highly organized and potentially sophisticated but that did not develop industry and probably any purely ocean-based lifeforms. The focus is thus on the period between the emergence of complex life on land in the Devonian (∼400Ma) in the Paleozoic era and the mid-Pliocene (∼4Ma).

2 THE GEOLOGICAL FOOTPRINT OF THE ANTHROPOCENE

While an official declaration of the Anthropocene as a unique geological era is still pending (Crutzen, 2002; Zalasiewicz et al., 2017), it is already clear that our human efforts will impact the geologic record being laid down today (Waters et al., 2014). Some of the discussion of the specific boundary that will define this new period is not relevant for our purposes because the markers proposed (ice core gas concentrations, short-half-lived radioactivity, the Columbian exchange) (e.g. Lewis & Maslin, 2015; Hamilton, 2016) are not going to be geologically stable or distinguishable on multi-million year timescales. However, there are multiple changes that have already occurred that will persist. We discuss a number of these below.

There is an interesting paradox in considering the Anthropogenic footprint on a geological timescale. The longer human civilization lasts, the larger the signal one would expect in the record. However, the longer a civilization lasts, the more sustainable its practices would need to have become in order to survive. The more sustainable a society (e.g. in energy generation, manufacturing, or agriculture) the smaller the footprint on the rest of the planet. But the smaller the footprint, the less of a signal will be embedded in the geological record. Thus the footprint of civilization might be self-limiting on a relatively short time-scale. To avoid speculating about the ultimate fate of humanity, we will consider impacts that are already clear, or that are foreseeable under plausible trajectories for the next century (e.g. Köhler, 2016; Nazarenko et al., 2015).

We note that effective sedimentation rates in ocean sediment for cores with multi-million-year old sediment are on the order of a few cm/1000 years at best, and while the degree of bioturbation may smear a short period signal, the Anthropocene will likely only appear as a section a few cm thick, and appear almost instantaneously in the record.

2.1 Stable isotope anomalies of carbon, oxygen, hydrogen and nitrogen

Since the mid-18th Century, humans have released over 0.5 trillion tons of fossil carbon via the burning of coal, oil and natural gas (Le Quéré et al., 2016), at a rate orders of magnitude faster than natural long-term sources or sinks. In addition, there has been widespread deforestation and addition of carbon dioxide into the air via biomass burning. All of this carbon is biological in origin and is thus depleted in ^{13}C compared to the much larger pool of inorganic carbon (Revelle & Suess, 1957). Thus the ratio of ^{13}C to ^{12}C in the atmosphere, ocean and soils is decreasing (an impact known as the "Suess Effect" (Quay et al., 1992)) with a current change of around -1‰ $\delta^{13}C$ since the pre-industrial (Böhm et al., 2002; Eide et al., 2017) in the surface ocean and atmosphere (figure 1a).

As a function of the increase of fossil carbon into the system, augmented by black carbon changes, other non-CO_2 trace greenhouse gases (like N_2O, CH_4 and CFCs), global industrialization has been accompanied by a warming of about 1°C so far since the mid 19th Century (GISTEMP Team, 2016; Bindoff et al., 2013). Due to the temperature-related fractionation in the formation of carbonates (Kim & O'Neil, 1997) (-0.2‰ $\delta^{18}O$ per °C) and strong correlation in the extra-tropics between temperature and $\delta^{18}O$ (between 0.4 and 0.7‰ per °C) (and roughly 8× as sensitive for deuterium isotopes relative to hydrogen (δD)), we expect this temperature rise to be detectable in surface ocean carbonates (notably foraminifera), organic biomarkers, cave records (stalactites), lake ostracods and high-latitude ice cores, though only the first two of these will be retrievable in the time-scales considered here.

The combustion of fossil fuel, the invention of the Haber-Bosch process, the large-scale application of nitrogenous fertilizers, and the enhanced nitrogen fixation associated with cultivated plants, have caused a profound impact on nitrogen cycling (Canfield et al., 2010), such that $\delta^{15}N$ anomalies are already detectable in sediments remote from civilization (Holtgrieve et al., 2011).

2.2 Sedimentological records

There are multiple causes of a greatly increased sediment flow in rivers and therefore in deposition in coastal environments. The advent of agriculture and associated deforestation have lead to large increases in soil erosion (Goudie, 2000; Committee on 21st Century Systems Agriculture, 2010). Furthermore, canalization of rivers (such as the Mississippi) have led to much greater oceanic deposition of sediment than would otherwise have occurred. This tendency is mitigated somewhat by concurrent increases in river dams which reduce sediment flow downstream. Additionally, increasing temperatures and atmospheric water vapor content have led to greater intensity of precipitation (Kunkel et al., 2013) which, on its own, would also lead to greater erosion, at least regionally. Coastal erosion is also on the increase as a function of rising sea level, and in polar regions is being enhanced by reductions in sea ice and thawing permafrost (Overeem et al., 2011).

In addition to changes in the flux of sediment from land to ocean, the composition of the sediment will also change. Due to the increased dissolution of CO_2 in the ocean as a function of anthropogenic CO_2 emissions, the upper ocean is acidifying (a 26% increase in H^+ or 0.1 pH decrease since the 19th Century) (Orr et al., 2005). This will lead to an increase in $CaCO_3$ dissolution within the sediment that will last until the ocean can neutralize the increase. There will also be important changes in mineralogy (Zalasiewicz et al., 2013; Hazen et al., 2017). Increases in continental weathering are also likely to change ratios of strontium and osmium (e.g. $^{87}Sr/^{86}Sr$ and $^{187}Os/^{188}Os$ ratios) (Jenkyns, 2010).

As discussed above, nitrogen load in rivers is increasing as a function of agricultural practices. This in turn is leading to more microbial activity in the coastal ocean which can deplete dissolved oxygen in the water column (Diaz & Rosenberg, 2008), and recent syntheses suggests a global decline already of about 2% (Schmidtko et al., 2017; Ito et al., 2017). This in turn is leading to an expansion of the oxygen minimum zones, greater ocean anoxia, and the creation of so-called "dead-zones" (Breitburg et al., 2018). Sediment within these areas will thus have greater organic content and less bioturbation (Tyrrell, 2011). The ultimate extent of these dead zones is unknown.

Furthermore, anthropogenic fluxes of lead, chromium, antimony, rhenium, platinum group metals, rare earths and gold, are now much larger than their natural sources (Gałuszka et al., 2013; Sen & Peucker-Ehrenbrink, 2012), implying that there will be a spike in fluxes in these metals in river outflow and hence higher concentrations in coastal sediments.

2.3 Faunal radiation and extinctions

The last few centuries have seen significant changes in the abundance and spread of small animals, particularly rats, mice, and cats etc., that are associated with human exploration and biotic exchanges. Isolated populations almost everywhere have now been superseded in many respects by these invasive species. The fossil record will likely indicate a large faunal radiation of these indicator species at this point. Concurrently, many other species have already, or are likely to become, extinct, and their disappearance from the fossil record will be noticeable. Given the perspective from many million years ahead, large mammal extinctions that occurred at the end of the last ice age will also associated with the onset of the Anthropocene.

2.4 Non-naturally occurring synthetics

There are many chemicals that have been (or were) manufactured industrially that for various reasons can spread and persist in the environment for a long time (Bernhardt et al., 2017). Most notably, persistent organic pollutants (POPs) (organic molecules that are resistant to degradation by chemical, photo-chemical or biological processes), are known to have spread across the world (even to otherwise pristine environments) (Beyer et al., 2000). Their persistence is often tied to being halogenated organics since the bond strength of C-Cl (for instance) is much stronger than C-C. For instance, polychlorinated biphenyls (PCBs) are known to have lifetimes of many hundreds of years in river sediment (Bopp, 1979). How long a detectable signal would persist in ocean sediment is, however, unclear.

Other chlorinated compounds may also have the potential for long-term preservation, specifically chloro-fluoro-carbons (CFCs) and related compounds. While there are natural sources for the most stable compound (CF_4), there are only anthropogenic sources for C_2F_6 and SF_6, the next most stable compounds. In the atmosphere, their sink via photolytic destruction in the stratosphere limits their lifetimes to a few thousand years (Ravishankara et al., 1993). The compounds do dissolve in the the ocean and can be used as tracers of ocean circulation, but we are unaware of studies indicating how long these chemicals might survive and/or be detectable in ocean sediment given some limited evidence for microbial degradation in anaerobic environments (Denovan & Strand, 1992).

Other classes of synthetic biomarkers may also persist in sediments. For instance, steroids, leaf waxes, alkenones, and lipids can be preserved in sediment for many millions of years (i.e Pagani et al., 2006). What might distinguish naturally occurring biomarkers from synthetics might be the chirality of the molecules. Most total synthesis pathways do not discriminate between D- and L-chirality, while biological processes are almost exclusively monochiral (Meierhenrich, 2008) (for instance, naturally occurring amino acids are all L-forms, and almost all sugars are D-forms). Synthetic steroids that do not have natural counterparts are also now ubiquitous in water bodies.

2.5 Plastics

Since 1950, there has been a huge increase in plastics being delivered into the ocean (Moore, 2008; Eriksen et al., 2014). Although many common forms of plastic (such as polyethylene and polypropylene) are buoyant in sea water, and even those that are nominally heavier than water may be incorporated into flotsam that remains at the surface, it is already clear that mechanical erosional processes will lead to the production of large amounts of plastic micro and nano-particles (Cozar et al., 2014; Andrady, 2015). Surveys have shown increasing amounts of plastic 'marine litter' on the seafloor from coastal areas to deep basins and the Arctic (Pham et al., 2014; Tekman et al., 2017). On beaches, novel aggregates "plastiglomerates" have been found where plastic-containing debris comes into contact with high temperatures (Corcoran et al., 2014).

The degradation of plastics is mostly by solar ultra- violet radiation and in the oceans occurs mostly in the photic zone (Andrady, 2015) and is notably temperature dependent (Andrady et al., 1998) (other mechanisms such as thermo-oxidation or hydrolysis do not readily occur in the ocean).

The densification of small plastic particles by fouling organisms, ingestion and incorporation into organic 'rains' that sink to the sea floor is an effective delivery mechanism to the seafloor, leading to increasing accumulation in ocean sediment where degradation rates are much slower (Andrady, 2015). Once in the sediment, microbial activity is a possible degradation pathway (Shah et al., 2008) but rates are sensitive to oxygen availability and suitable microbial communities.

As above, the ultimate long-term fate of these plastics in sediment is unclear, but the potential for very long term persistence and detectability is high.

2.6 Transuranic elements

Many radioactive isotopes that are related to anthropogenic fission or nuclear arms, have half-lives that are long, but not long enough to be relevant here. However, there are two isotopes that are potentially long-lived enough. Specifically, Plutonium-244 (half-life 80.8 million years) and Curium-247 (half life 15 million years) would be detectable for a large fraction of the relevant time period if they were deposited in sufficient quantities, say, as a result of a nuclear weapon exchange. There are no known natural sources of ^{244}Pu outside of supernovae.

Attempts have been made to detect primordial ^{244}Pu on Earth with mixed success (Hoffman et al., 1971; Lachner et al., 2012), indicating the rate of actinide meteorite accretion is small enough (Wallner et al., 2015) for this to be a valid marker in the event of a sufficiently large nuclear exchange. Similarly, ^{247}Cm is present in nuclear fuel waste and as a consequence of a nuclear explosion.

Anomalous isotopic ratios in elements with long-lived radioactive isotopes are also possible signatures, for instance, lower than usual ^{235}U ratios, and the presence of expected daughter products, in uranium ores in the Franceville Basin in the Gabon have been traced to naturally occurring nuclear fission in oxygenated, hydrated rocks around 2 Gya (Gauthier-Lafaye et al., 1996).

2.7 Summary

The Anthropocene layer in ocean sediment will be abrupt and multi-variate, consisting of seemingly concurrent specific peaks in multiple geochemical proxies, biomarkers, elemental composition, and mineralogy. It will likely demarcate a clear transition of faunal taxa prior to the event compared to afterwards. Most of the individual markers will not be unique in the context of Earth history as we demonstrate below, but the combination of tracers may be. However, we speculate that some specific tracers that would be unique, specifically persistent synthetic molecules, plastics, and (potentially) very long-lived radioactive fallout in the event of nuclear catastrophe. Absent those markers, the uniqueness of the event may well be seen in the multitude of relatively independent fingerprints as opposed to a coherent set of changes associated with a single geophysical cause.

3 ABRUPT PALEOZOIC, MESOZOIC AND CENOZOIC EVENTS

The summary for the Anthropocene fingerprint above suggests that similarities might be found in (geologically) abrupt events with a multi-variate signature. In this section we review a partial selection of known events in the paleo-record that have some similarities to the hypothesized eventual anthropogenic signature. The clearest class of event with such similarities are the hyperthermals, most notably the Paleocene-Eocene Thermal Maximum (56 Ma) (McInerney & Wing, 2011), but this also includes smaller hyperthermal events, ocean anoxic events in the Cretaceous and Jurassic, and significant (if less well characterized) events of the Paleozoic. We don't consider of events (such as the K-T extinction event, or the Eocene-Oligocene boundary) where there are very clear and distinct causes (asteroid impact combined with massive volcanism(Vellekoop et al., 2014), and the onset of Antarctic glaciation(Zachos et al., 2001) (likely linked to the opening of Drake Passage(Cristini et al., 2012)), respectively). There may be more such events in the record but that are not included here simply because they may not have been examined in detail, particularly in the pre-Cenozoic.

3.1 The Paleocene-Eocene Thermal Maximum (PETM)

The existence of an abrupt spike in carbon and oxygen isotopes near the Paleocene/Eocene transition (56 Ma) was first noted by Kennett & Stott (1991) and demonstrated to be global by Koch et al. (1992). Since then, more detailed and high resolution analyses on land and in the ocean have revealed a fascinating sequence of events lasting 100–200 kyr and involving a rapid input (in perhaps less than 5 kyr(Turner et al., 2017)) of exogenous carbon into the system (see review by McInerney & Wing, 2011), possibly related to the intrusion of the North American Igneous Province into organic sedimentsStorey et al. (2007). Temperatures rose 5–7°C (derived from multiple proxies (Tripati & Elderfield, 2004)), and there was a negative spike in carbon isotopes (>3‰), and decreased ocean carbonate preservation in the upper ocean. There was an increase in kaolinite (clay) in many sediments (Schmitz et al., 2001), indicating greater erosion, though evidence for a global increase is mixed. During the PETM 30–50% of benthic foraminiferal taxa became extinct, and it marked the time of an important mammalian (Aubry et al., 1998) and lizard (Smith, 2009) expansion across North America. Additionally, many metal abundances (including V, Zn, Mo, Cr) spiked during the event (Soliman et al., 2011).

3.2 Eocene events

In the 6 million years following the PETM, there are a number of smaller, though qualitatively similar, hyperthermal events seen in the record (Slotnick et al., 2012). Notably, the Eocene Thermal Maximum 2 event (ETM-2), and at least four other peaks are characterized by significant negative carbon isotope excursions, warming and relatively high sedimentation rates driven by increases in terrigenous input (D'Onofrio et al., 2016). Arctic conditions during ETM-2 show evidence of warming, lower salinity, and greater anoxia (Sluijs et al., 2009). Collectively these events have been denoted Eocene Layers of Mysterious Origin (ELMOs)[2].

Around 40 Ma, another abrupt warming event occurs (the Mid-Eocene Climate Optimum (MECO)), again with an accompanying carbon isotope anomaly (Galazzo et al., 2014).

[2] While it is tempting to read something into the nomenclature of these events, it should be remembered that most things that happened 50 million years ago will forever remain somewhat mysterious.

3.3 Cretaceous and Jurassic Ocean Anoxic Events

First identified by Schlanger & Jenkyns (1976), ocean anoxic events (OAEs), identified by periods of greatly increased organic carbon deposition and laminated black shale deposits, are times when significant portions of the ocean (either regionally or globally) became depleted in dissolved oxygen, greatly reducing aerobic bacterial activity. There is partial (though not ubiquitous) evidence during the larger OAEs for euxinia (when the ocean column becomes filled with hydrogen sulfide (H_2S)) (Meyer & Kump, 2008).

There were three major OAEs in the Cretaceous, the Weissert event (132 Ma) (Erba et al., 2004), OAE-1a around 120 Ma lasting about 1 Myr and another OAE-2 around 93 Ma lasting around 0.8 Myr (Kerr, 1998; Li et al., 2008; Malinverno et al., 2010; Li et al., 2017). At least four other minor episodes of organic black shale production are noted in the Cretaceous (the Faraoni event, OAE-1b, 1d and OAE-3) but seem to be restricted to the proto-Atlantic region (Takashima et al., 2006; Jenkyns, 2010). At least one similar event occurred in the Jurassic (183 Ma) (Pearce et al., 2008).

The sequence of events during these events have two distinct fingerprints possibly associated with the two differing theoretical mechanisms for the events. For example, during OAE-1b, there is evidence of strong stratification and a stagnant deep ocean, while for OAE-2, the evidence suggests an decrease in stratification, increased upper ocean productivity and an expansion of the oxygen minimum zones (Takashima et al., 2006).

At the onset of the events (fig. 1c), there is often a significant negative excursion in δ^{13}C (as in the PETM), followed by a positive recovery during the events themselves as the burial of (light) organic carbon increased and compensated for the initial release (Jenkyns, 2010; Naafs et al., 2016; Mutterlose et al., 2014; Kuhnt et al., 2011). Causes have been linked to the crustal formation/tectonic activity and enhanced CO_2 (or possibly CH_4) release, causing global warmth (Jenkyns, 2010). Increased seawater values of ^{87}Sr/^{86}Sr and ^{187}Os/^{188}Os suggest increased runoff, greater nutrient supply and consequently higher upper ocean productivity (Jones, 2001). Possible hiatuses in some OAE 1a sections are suggestive of an upper ocean dissolution event (Bottini et al., 2015).

Other important shifts in geochemical tracers during the OAEs include much lower nitrogen isotope ratios (δ^{15}N), increases in metal concentrations (including As, Bi, Cd, Co, Cr, Ni, V) (Jenkyns, 2010). Positive shifts in sulfur isotopes are seen in most OAEs, with a curious exception in OAE-1a where the shift is negative (Turchyn et al., 2009).

3.4 Early Mesozoic and Late Paleozoic events

Starting from the Devonian period, there have been several major abrupt events registered in terrestrial sections. The sequences of changes and the comprehensiveness of geochemical analyses are less well known than for later events, partly due to the lack of existing ocean sediment, but these have been identified in multiple locations and are presumed to be global in extent.

The Late Devonian extinction around 380–360 Ma, was one of the big five mass extinctions. It's associated with black shales and ocean anoxia (Algeo & Scheckler, 1998), stretching from the Kellwasser events (∼378 Ma) to the Hangenberg event at the Devonian-Carboniferous boundary (359 Ma) (Brezinski et al., 2009; Vleeschouwer et al., 2013).

In the late Carboniferous, around 305 Ma the Pangaean tropical rainforests collapsed (Sahney et al., 2010). This was associated with a shift toward drier and cooler climate, and possibly a reduction in atmospheric oxygen, leading to extinctions of some mega-fauna.

Lastly, the end-Permian extinction event (252 Ma) lasted about 60 kyr was accompanied by an initial decrease in carbon isotopes (-5–7‰), significant global warming and extensive deforestation and wildfires (Krull & Retallack, 2000; Shen et al., 2011; Burgess et al., 2014) associated with widespread ocean anoxia and euxinia (Wignall & Twitchett, 1996). Pre-event spikes in nickel (Ni) have also been reported (Rothman et al., 2014).

4 DISCUSSION AND TESTABLE HYPOTHESES

There are undoubted similarities between previous abrupt events in the geological record and the likely Anthropocene signature in the geological record to come. Negative, abrupt δ^{13}C excursions, warmings, and disruptions of the nitrogen cycle are ubiquitous. More complex changes in biota, sedimentation and mineralogy are also common. Specifically, compared to the hypothesized

Anthropocene signature, almost all changes found so far for the PETM are of the same sign and comparable magnitude. Some similarities would be expected if the main effect during any event was a significant global warming, however caused. Furthermore, there is evidence at many of these events that warming was driven by a massive input of exogeneous (biogenic) carbon, either as CO_2 or CH_4. At least since the Carboniferous (300–350 Ma), there has been sufficient fossil carbon to fuel an industrial civilization comparable to our own and any of these sources could provide the light carbon input. However, in many cases this input is contemporaneous to significant episodes of tectonic and/or volcanic activity, for instance, the coincidence of crustal formation events with the climate changes suggest that the intrusion of basaltic magmas into organic-rich shales and/or petroleum-bearing evaporites (Storey et al., 2007; Svensen et al., 2009; Kravchinsky, 2012) may have released large quantities of CO_2 or CH_4 to the atmosphere. Impacts to warming and/or carbon influx (such as increased runoff, erosion etc.) appear to be qualitatively similar whenever in the geological period they occur. These changes are thus not sufficient evidence for prior industrial civilizations.

Current changes appear to be significantly faster than the paleoclimatic events (figure 1), but this may be partly due to limitations of chronology in the geological record. Attempts to time the length of prior events have used constant sedimentation estimates, or constant-flux markers (e.g. ^3He (McGee & Mukhopadhyay, 2012)), or orbital chronologies, or supposed annual or seasonal banding in the sediment (Wright & Schaller, 2013). The accuracy of these methods suffer when there are large changes in sedimentation or hiatuses across these events (which is common), or rely on the imperfect identification of regularities with specific astronomical features (Pearson & Nicholas, 2014; Pearson & Thomas, 2015). Additionally, bioturbation will often smooth an abrupt event even in a perfectly preserved sedimentary setting. Thus the ability to detect an event onset of a few centuries (or less) in the record is questionable, and so direct isolation of an industrial cause based only on apparent timing is also not conclusive.

The specific marker of human industrial activity discussed above (plastics, synthetic pollutants, increased metal concentrations etc.) are however a consequence of the specific path human society and technology has taken, and the generality of that pathway for other industrial species is totally unknown. Large-scale energy harnessing is potentially a more universal indicator, and given the large energy density in carbon-based fossil fuel, one might postulate that a light δ^{13}C signal might be a common signal. Conceivably, solar, hydro or geothermal energy sources could have been tapped preferentially, and that would greatly reduce any geological footprint (as it would ours). However any large release of biogenic carbon whether from methane hydrate pools or volcanic intrusions into organic rich sediments, will have a similar signal. We therefore have a situation where the known unique markers might not be indicative, while the (perhaps) more expected markers are not sufficient.

We are aware that raising the possibility of a prior industrial civilization as a driver for events in the geological record might lead to rather unconstrained speculation. One would be able to fit any observations to an imagined civilization in ways that would be basically unfalsifiable. Thus, care must be taken not to postulate such a cause until actually positive evidence is available. The Silurian hypothesis cannot be regarded as likely merely because no other valid idea presents itself.

We nonetheless find the above analyses intriguing enough to motivate some additional research. Firstly, despite copious existing work on the likely Anthropocene signature, we recommend further synthesis and study on the persistence of uniquely industrial byproducts in ocean sediment environments. Are there other classes of compounds that will leave unique traces in the sediment geochemistry on multi-million year timescales? In particular, will the byproducts of common plastics, or organic long-chain synthetics, be detectable?

Secondly, and this is indeed more speculative, we propose that a deeper exploration of elemental and compositional anomalies in extant sediments spanning previous events be performed (although we expect that far more information has been obtained about these sections than has been referenced here). Oddities in these sections have been looked for previously as potential signals of impact events (successfully for the K-T boundary event, not so for any of the events mentioned above), ranging from iridium layers, shocked quartz, micro-tectites, magnetites etc. But it may be that a new search and new analyses with the Silurian hypothesis in mind might reveal more. Anomalous behaviour in the past might be more clearly detectable in proxies normalized by weathering fluxes or other constant flux proxies in order to highlight times when productivity or metal production might have been artificially enhanced. Thirdly, should any unexplained anomalies be found, the question of whether there are candidate species in the fossil record may become more relevant, as might questions about their ultimate fate.

An intriguing hypothesis presents itself should any of the initial releases of light carbon described above indeed be related to a prior industrial civilization. As discussed in section 3.3, these releases often triggered episodes of ocean anoxia (via increased nutrient supply) causing a massive burial of organic matter, which eventually became source strata for further fossil fuels. Thus the prior industrial activity would have actually given rise to the potential for future industry via their own demise. Large scale anoxia, in effect, might provide a self-limiting but self- perpetuating feedback of industry on the planet. Alternatively, it may be just be a part of a long term episodic natural carbon cycle feedback on tectonically active planets.

Perhaps unusually, the authors of this paper are not convinced of the correctness of their proposed hypothesis. Were it to be true it would have profound implications and not just for astrobiology. However most readers do not need to be told that it is always a bad idea to decide on the truth or falsity of an idea based on the consequences of it being true. While we strongly doubt that any previous industrial civilization existed before our own, asking the question in a formal way that articulates explicitly what evidence for such a civilization might look like raises its own useful questions related both to astrobiology and to Anthropocene studies. Thus we hope that this paper will serve as motivation to improve the constraints on the hypothesis so that in future we may be better placed to answer our title question.

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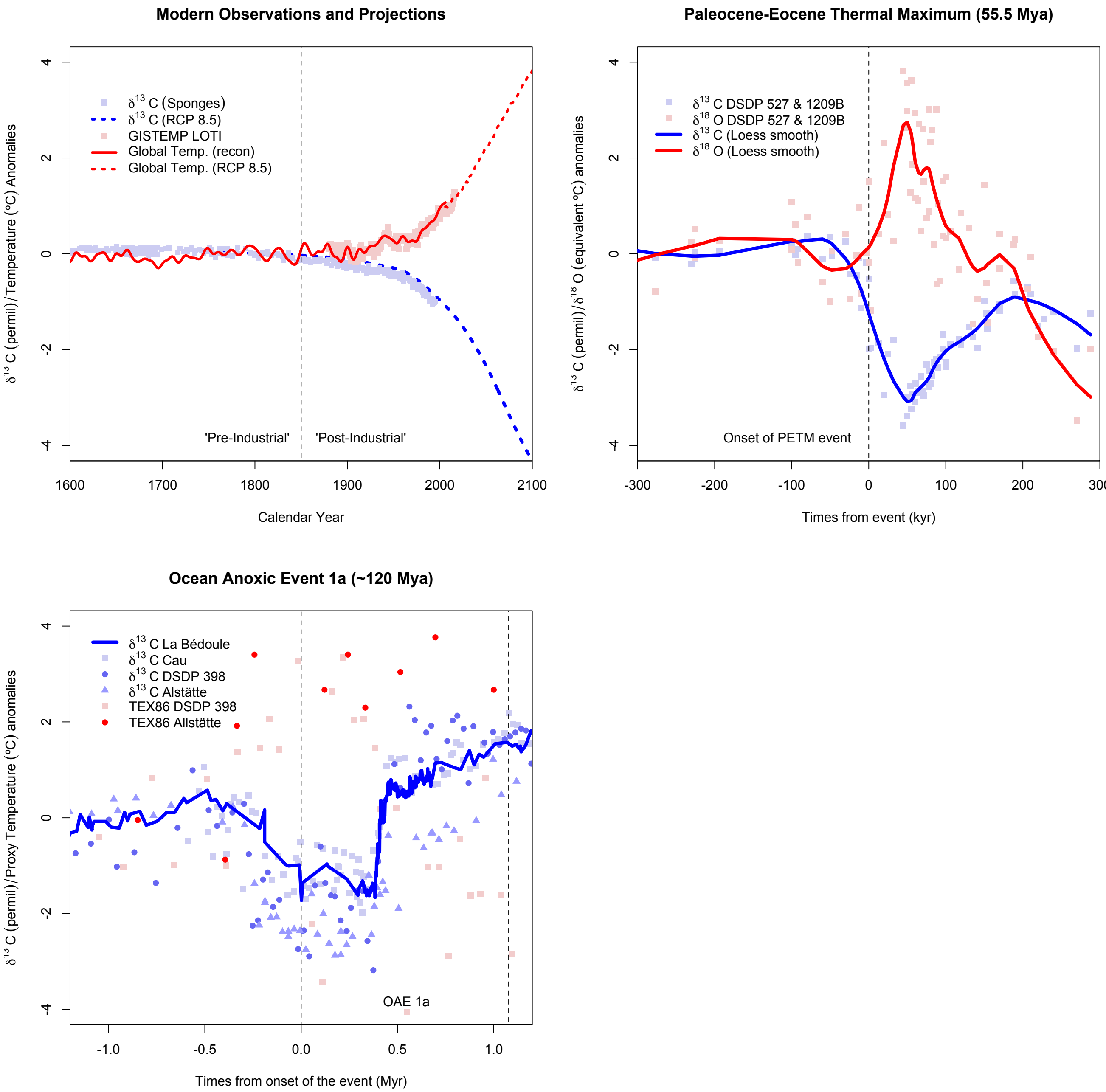

Figure 1. Illustrative stable carbon isotopes and temperature (or proxy) profiles across three periods. a) The modern era (from 1600 CE with projections to 2100). Carbon isotopes are from sea sponges (Böhm et al., 2002), and projections from Köhler (2016). Temperatures are from Mann et al. (2008) (reconstructions), GISTEMP (Hansen et al., 2010) (instrumental) and projected to 2100 using results from Nazarenko et al. (2015). Projections assume trajectories of emissions associated with RCP8.5 (van Vuuren et al., 2011). b) The Paleocene-Eocene Thermal Maximum (55.5 Mya). Data from two DSDP cores (589 and 1209B) (Tripati & Elderfield, 2004) are used to estimate anomalous isotopic changes and a loess smooth with a span of 200 kya is applied to make the trends clearer. Temperatures changes are estimated from observed $\delta^{18}\mathrm{O}_{carbonate}$ using a standard calibration (Kim & O'Neil, 1997). c) Oceanic Anoxic Event 1a (about 120 Myr). Carbon isotopes are from the La Bédoule and Cau cores from the paleo-Tethys (Kuhnt et al., 2011; Naafs et al., 2016) aligned as in Naafs et al. (2016) and placed on an approximate age model. Data from Alstätte (Bottini & Mutterlose, 2012) and DSDP Site 398 (Li et al., 2008) are aligned based on coherence of the $\delta^{13}C$ anomalies. Temperature change estimates are derived from TEX86 (Mutterlose et al., 2014; Naafs et al., 2016). Note that the y-axis spans the same range in all three cases, while the timescales vary significantly.